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THE ROYAL ASTRONOMICAL SOCIETY OF CANADA

DEVOTED TO THE ADVANCEMENT OF ASTRONOMY AND ALLIED SCIENCES

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Articles PAGE

The Structure of the Earth as Revealed by Seismology (with Plates V-VII) ..... *Ernest A. Hodgson* 273

The Centennial Celebration of the Loomis Observatory ..... *Helen Sawyer Hogg* 299

Meteor News

The Origin of Meteoric Material ..... *P.M.M.* 304

Review of Publications

Spectral Atlas of Bright Stars of the Northern and Southern Hemisphere, by Josef Klepesta (*P.M.M.*)—The Nature of Variable Stars, by Paul W. Merrill (*C.A.C.*)—A Hundred Years of Astronomy, by Reginald L. Waterfield (*C.A.C.*)—Leben und Wirken des Johannes Müller gennant Regiomontanus, by Ernst Zinner (*C.A.C.*) 309

Notes and Queries

Congratulations—How many Pleiades can you see?—The Great Aurora of January 25-26; its Audibility (*C.A.C.*) 313

Meetings of the Society

At Toronto—At Vancouver 315

Radio Talks over CFCT, Victoria, B.C.

Big Stars—Little Stars 317

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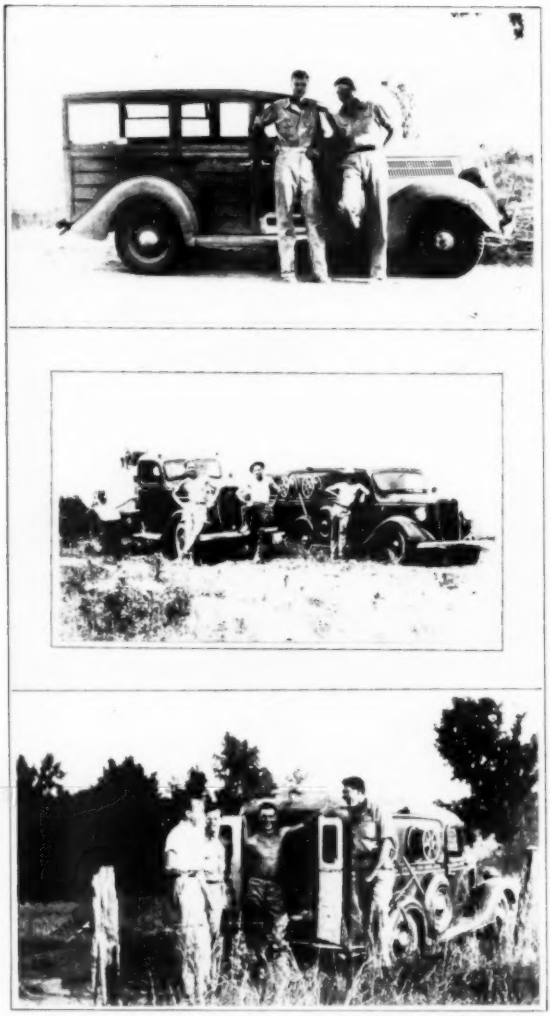

Fig. 13.—Automotive equipment.

Top: The surveying truck.
Middle: The explosives truck and the recording truck.
Bottom: Nearer view of recording truck.

Fig. 14.—Seismic shooting.

Top left: Attaching dynamite to loading pole and preparing firing cap and wires.
Top right: Lowering charge with loading poles.
Bottom left: Method of measuring dynamite charges by cutting sections from 2½ lb. sticks.
Bottom right: Set up for a regulation shot (in this case bedded with an overload of water).

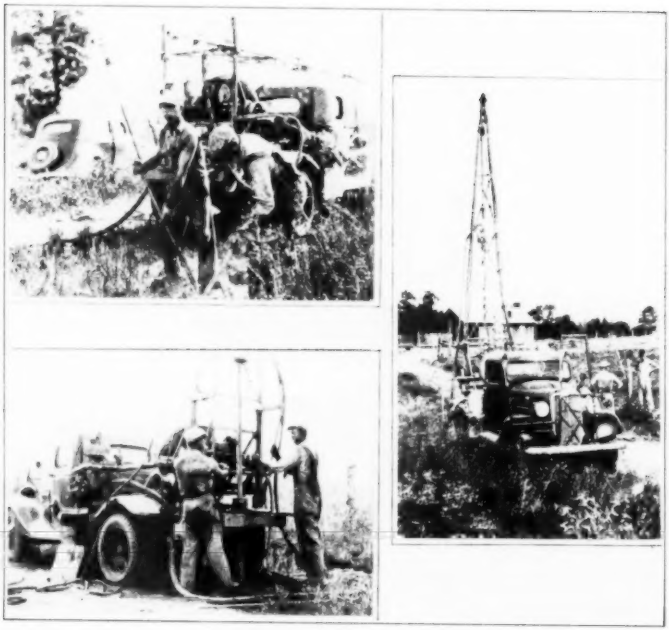

Fig. 15.—Drilling shot holes.

Left top: Digging sump hole for flushing water.
Left bottom: Applying pressure to rotating drill.
Right: Truck with drilling mast hoisted.

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THE STRUCTURE OF THE EARTH AS REVEALED BY SEISMOLOGY

By ERNEST A. HODGSON

(with Plates V, VI, VII)

YOU remember what Doc said of Dopey*, "He don't know if he can talk or not; he ain't never tried." For the same reason I do not know whether I can succeed or not—having never tried to deal with this phase of seismology before a general audience—but I hope it will be possible for me, without recourse to technical details, to present a clear and convincing picture of the means by which we have learned something of "The Structure of the Earth as Revealed by Seismology."

As usual, "The Greeks had a word for it." Their word for earthquake was *seismos*; hence, seismology, the study of earthquakes. There is no reason, however, why seismology should be "all Greek" to the layman.

Why study earthquakes? Coming closer home, let us ask the very pertinent, perhaps sometimes disconcerting, question, "Why study earthquakes in Canada?" Throughout this presentation as opportune moments present themselves we shall note phases of the answer—in a series of brief asides.

Earthquakes merit study. According to good authority approximately 800 earthquakes, strong enough to destroy cities and towns, have occurred on land since the beginning of the Christian era. History shows that an average of 30,000 persons have been killed

*Walt Disney's, "Snow White and the Seven Dwarfs."

each year during the past two centuries by these phenomena. More than 20,000 earthquakes occur each year; a widely recorded shock each fourteen hours; a destructive earthquake each six and one-half days—on the average of course.

Perhaps, then, it may be assumed without argument that major earthquakes *should* be studied. Why be prepared to study them in Canada? Since Cartier's first voyage in 1534 an earthquake of major proportions has occurred, in Canada, every fifty or sixty years—on an average. These earthquakes have been, in general, more severe than the one which, in 1933, caused fifty million dollars damage at Long Beach, California. It has just so happened that structures liable to damage were not situated near the origins or *epicentres* of these shocks. Canada is building up rapidly; the earthquakes will continue. You may draw the obvious and inevitable conclusion.

It was an attempt to ameliorate in some measure the damage caused by earthquakes which led initially to their being studied by scientifically trained men. Progress was slow at first, but there has gradually evolved a branch of the subject which may be called "engineering seismology". Considerable progress has been made of late years, particularly in Japan, in Italy, and in California. It is now possible to design houses which, except in the most extreme cases, will not be destroyed by an earthquake, will not be set on fire thereby, and will not kill their inmates or passers-by with falling debris. Moreover, the specifications for such structures are now written into some building codes, for example those in parts of California.

But, as someone once remarked that Kipling said—"That is another story." It is well to remember that this presentation is limited to a very sketchy *résumé* of but one phase of seismology. Much will be left unsaid. These "other stories" are not unimportant but at this time we must pass them over. They form part of the answer to the question, "Why study earthquakes?" but not part of the subject, "The Structure of the Earth as Revealed by Seismology."

Taking for granted part of that which we shall later find to have been revealed by seismology, we may consider the earth to be a sphere consisting of three main divisions: a central *core*,

with a radius of about 2200 miles; surrounded by the *mantle*, a concentric sphere a little less than 1800 miles thick; which is, in turn, surrounded by a *crust* of a varying thickness which may be set down roughly as 25 miles. We take in our stride the responsibility for the approximations as to the sphericity of the earth and the various dimensions given. We shall discuss the theory and the technique of determining earth structure under four different conditions and in the order named: the crust; the mantle; the core; and, finally, returning again to the upper part of the crust—that region which is within reach of the drill.

One of the first things that men learned about the crust of the earth is that it does not have uniform stability. Frequent earthquakes occur only in certain seismic zones. One of the routine activities of seismological investigation is that of locating as accurately as possible all recorded earthquakes. To do this, international co-operation is necessary. At the present time more than 250 seismic stations are in operation, reporting regularly to each other and to a central station at Oxford, England, where an agency under the joint auspices of that University and of the International Union of Geodesy and Geophysics determines the position of all locatable shocks and publishes a statistical summary of the data. We now know that the most active seismic regions of the world may be defined as a belt about the Pacific with an offshoot zone across Asia and Europe north of India and along the north shore of the Mediterranean to meet another belt running north and south through the relatively shoal water of the mid-Atlantic. We know, further, that *all* earthquakes are not confined to these more active belts. We have very good reason for saying that there is no region of the earth in which a major earthquake might *not* take place. This international service was begun in 1895 and has been growing steadily ever since. Canada has participated since 1897.

How then can seismic stations determine from their records where an earthquake has occurred? It would take much too long to sketch the slow degrees by which men learned to construct seismographs and deduce the method of interpreting from their records the distance from the recording station to the source of an earthquake. The abstract mathematical foundations of the theory were laid as early as 1849, but it was not until 1889 that, by chance,

the first record of an earthquake was made at a distance. At that time an earthquake in Japan was found to have been recorded on a very sensitive instrument at Potsdam, Germany, set up for the purpose of determining to what extent the earth itself has tides similar to though smaller than those caused on the sea. Not until 1900, however, was such a distant earthquake record interpreted to yield a value of the distance from station to origin.

Before explaining how distance can be read from the record, we must know just a little about the instrument known as a seismograph. Suppose someone asked you to describe a ladies' hat—not some particular hat—just a hat. That difficulty comparable with an attempt to describe the appearance of a typical seismograph. Such instruments vary in size from one you could hold in your hand to one which stands more than six feet high and weighs twenty tons. One thing, however, seismographs have in common. A relatively-heavy weight is held very delicately suspended from a framework which is, itself, in firm contact with the earth. When the earth moves, the weight stays behind as you tend to do when the street car starts suddenly. The relative motion of the weight and the frame attached to the earth is recorded continuously and gives the record. When the earth is at rest the record line is straight. When a shock impulse arrives, the line is deflected. At regularly-timed intervals, normally once a minute, a slight motion is given the recording mechanism so that a small, recognizable, offset (or, in some cases, a short interruption) occurs on the line. A diagram of one sort of seismograph is shown in Fig. 1 together with a small section of a record showing the timing marks. All we wish to emphasize here is that an instrument has been developed which enables the inertia of a weight to give us a record indicating that an impulse has arrived at the recording station and telling us the exact moment of its arrival.

The earth is an elastic body—almost as elastic as steel. That is to say, if any part of it be deformed by force, that deformation will vanish when the force is removed. It is the elastic properties of steel which, for example, cause a suspended bar of the material to give off a ringing note when struck by a hammer. It is the elastic properties of the earth which cause it to transmit earthquake waves.

As early as 1849 it was deduced mathematically that an elastic

body should transmit two kinds of waves and mathematical expressions for the speeds of the two waves were found. These two classes of waves are known as *longitudinal* and *transverse*. The first is propagated by the back-and-forth motion of the earth particles in the direction of the wave, somewhat after the manner in which a bump from an engine is transmitted down a long line of freight cars. The second is propagated by a transverse motion of adjacent

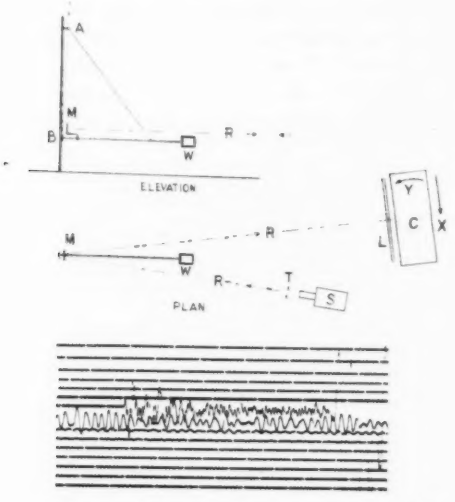

Fig. 1.—Schematic diagram of a typical horizontal seismograph and a section of a record, showing time breaks and an earthquake.

particles somewhat after the manner in which a water wave travels; the floating debris shows that the water particles move at right angles to the direction of propagation of the wave.

The difference in velocity depends on the elastic properties of the body through which the waves travel. For short distances it is a sort of neck and neck race. No laboratory is large enough to enable the waves to separate sufficiently for the fact to be established experimentally. So for many years there was no experimental

verification of the two types of waves. After earthquakes were registered at considerable distances, it was found that a second burst of energy showed on the record among the dying vibrations of the first impulse (see Fig. 2). The greater the distance from earthquake to station the greater was found to be the separation of these two impulses. It was finally established that these were the arrivals of the two types of waves which had left the origin of the earthquake together but had travelled at different speeds. The difference in time of arrival is thus a measure of the distance.

The two types of waves of which we have been speaking are designated, respectively, *P* and *S* waves by seismologists since, in point of time of arrival, they are primary and secondary. It is readily seen that, if observers possess a time-table showing the time

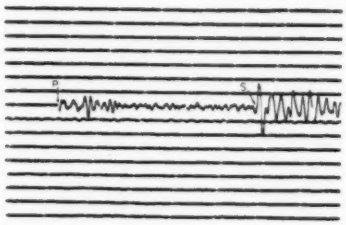

Fig. 2.—Section of a seismogram showing the *P* and *S* phases.

required for the *P*-wave to reach various distances on the earth's surface and a similar one for the *S*-wave, a table could be prepared showing the relation between $S-P$ times and the epicentral distances. The first table of this sort was prepared by Oldham in 1900, and since then a steady improvement has been effected. Such compilations are called *time-distance tables* or, if plotted on graph paper, *time-distance graphs*. Given the table, it is easily seen how the distances from each station to the epicentre can be deduced. Now, if it be known how far the epicentre lies from any station then the epicentre must lie on a circle drawn about that station with the proper distance radius. If the circles for all the stations be drawn, their point of intersection makes the x which marks the spot (see Fig. 3).

A well defined earthquake can be located no matter where it

may have occurred. Thus, routine statistical seismology is piling up accurate records of where earthquakes occur and when. Furthermore, we are now able to deduce the depth at which the shocks originate.

The point within the earth from which the earthquake energy is liberated is called the *focus*; the point vertically above it on the earth's surface is the *epicentre*. Now if the focus be on the surface we have what may be called, for want of a better name, a *normal*

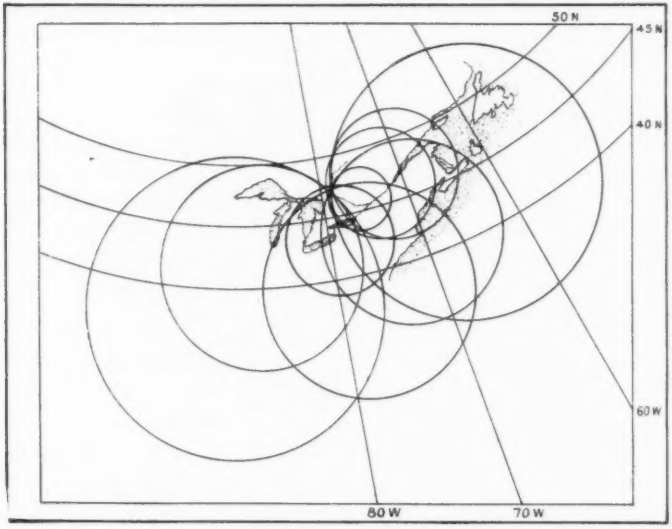

Fig. 3.—Intersection of distance circles indicating the epicentre of the Timiskaming earthquake of November 1, 1935.

earthquake. To simplify our discussion we shall from this point confine our attention to the *P*-wave—the first impulse on the record. Obviously, the time-distance graph of a normal earthquake begins at the zero-zero point—at the origin of co-ordinates. Suppose another earthquake should happen with the focus at a depth of, say, 100 miles. All distances for our time-distance graph are measured from the epicentre. The epicentre is thus at zero distance. The *time* required for the impulse *P* to reach the epicentre

at *distance* zero is in this case more than nothing and the time-distance graph must begin a certain distance up on the time axis, *i.e.*, it must begin above the graph for a normal earthquake. But, at the antipodes of the epicentre, the shock must arrive earlier for a deep focus than for a normal one and the second curve must here lie below the first. The curves must cross. If the focal depth were 200 miles the new time-distance graph would start even later and arrive earlier than before—and so for successively-greater depths of focus. A typical pair of graphs is shown in Fig. 4. *If the*

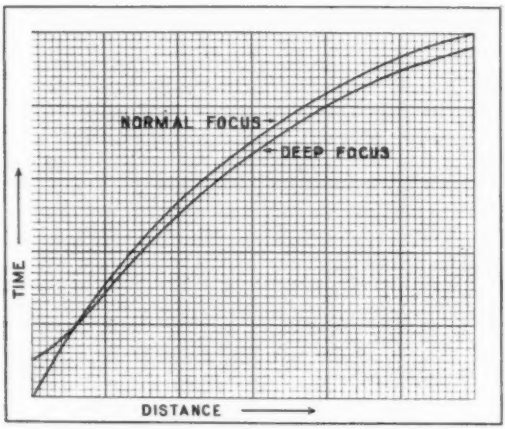

Fig. 4.—Characteristic form of the time-distance curve for normal focus and for deep focus.

arrival times of the P-wave at a sufficient number of stations can be obtained, it is possible to determine from such a set of curves not only the distance to the epicentre but also the focal depth. In passing, let us note that Canada with her great expanse of territory would leave a wide gap in many of these curves did she not maintain a certain number of stations at strategically spaced positions. Her seven stations are little enough coverage for a country of such dimensions.

Depths of focus as great as 500 miles and more have been established and are a distinct contribution to the knowledge of the

structure of the earth. They show that the earth can sustain built-up strain at depths previously considered impossible. We can no longer maintain that the crust alone is crystalline and that the mantle is plastic. At least the mantle is not plastic in the sense it was thought to be until deep focus earthquakes were established as a fact. Probably no contribution of the science has aroused a greater interest among those concerned with learning something of the structure of the earth.

But such depths are taking us into the mantle of the earth and we are not yet finished with our consideration of the problem of determining the structure of the crust. It is interesting to go back to an early experiment which is in a sense the beginning of our probing of the earth's crust by elastic waves. In 1859 Robert Mallet, an Irish investigator, undertook to measure the velocity of elastic waves caused by blasting in a quarry at Holyhead island. His methods were crude but carefully carried out and his distances were short—a little over a mile. He found velocities of from 825 to 1660 feet per second. In 1878 Henry Abbot, an officer of the United States army, carried out some experiments to determine the velocity of elastic waves caused by gunfire. His distances were greater than those of Mallet—of the order of thirteen miles. His deduced velocities were much greater—up to 5900 feet per second. Mallet learned of these results and disputed them. We need not go into details regarding the controversy further than to say that each being prepared to stand beside his respective determination the conclusion adopted was that the higher velocities of Abbot's experiment were the result of using greater explosions. In other words: the velocity of elastic waves depends on the intensity of the generating force. This conclusion was in error. It was considered doubtful at the time and led to further experiments. After some years sufficient data were obtained to establish the true explanation which we may now examine.

Suppose that the upper stratum of the earth transmits elastic waves at a velocity which is less than that for the deeper lying material. In this case, *deeper* means something of the order of fifty to a hundred feet. The diagram in Fig. 5 shows the approximate path of two rays of the waves propagated from an explosion at the surface. Let us take for granted that the rays are of the

form shown and concentrate on visualizing the speed with which the nose of the advancing wave radiates over the surface.

If the surface were a calm lake, we could see the water waves radiate in ever widening circles from the shock. Those waves would be *gravity* waves, not the *elastic* waves which we are now considering, but the same sort of ever-widening circles marks the progress of the energy transmitted by the earth. If the surface were covered with a thin layer of mercury we could actually see the nose of the disturbance spreading out from the source. If we were

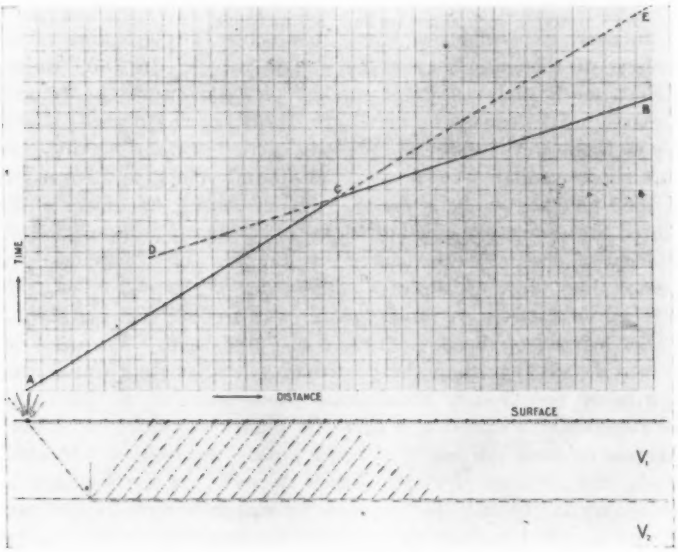

Fig. 5.—Diagram illustrating the refraction method of probing surface layered structure. Velocities in the upper and lower layers are respectively V_1 and V_2. At distance C the energy by surface and sub-surface paths arrives simultaneously. For lesser distances, the earlier arrival is by the surface path. For greater distances, the earlier arrival is by the sub-surface path. The critical angle a depends on the velocities V_1 and V_2 which are given by the two graph slopes. Having V_1, V_2, C, and a the thickness of the upper layer may be computed.

to put a dish of mercury on the ground at a not too great distance we could see a segment of the expanding circle pass over it. If we wish to know very exactly *when* the energy passes regularly-placed points on a line extending outward from the source to a considerable distance, say twenty miles or more, we place sensitive seismographs at those points and have them record on a strip of moving paper which carries time marks. In this way we can tell when the initial impulse reaches each station and, if the seismographs be properly designed, we can also discern the arrival of later impulses—points on the common radius through the source, of the familiar *circles within circles* which can be seen when gravity waves radiate from a stone thrown into still water.

A little reflection is sufficient to show that, near the source, the arrival of the wave at successive stations will be at the rate V_1, if we may so designate the velocity in the upper layer. At a particular distance from the source is some station at which the energy, travelling along the surface with velocity V_1, will arrive at the same instant as that which has travelled down to the surface of discontinuity at velocity V_1 along the under surface of that layer at velocity V_2, to a point from which it rose again to the surface with velocity V_1. The greater distance travelled is just compensated for, by part of the path being traversed at greater velocity.

We can readily see that to get from one point to another in New York City for short distances we can travel to better advantage by surface street car, but for greater distances we make up for the time spent in going down to the subway and climbing out at the other end by the higher speed with which the subway carries us. At some point not too far distant it would be an even race to go via the surface or via the subway; beyond that point the subway would be the quicker route.

Let us suppose that we are equipped with properly designed seismographs at each station, from the source outward. The records for the very near stations will show only one arrival—the wave through the surface layer. At a certain minimum distance (which depends on the angle with which the ray reaches the surface of discontinuity, which in turn depends on the ratio of the two velocities V_1 and V_2) energy will begin to arrive via the lower path; but it will arrive *after* the surface transmitted energy and will

appear on the record as a second impulse. Farther out will be a station at which the energy by the two paths arrives simultaneously. Beyond that point, the first impulse will be that arriving via the lower stratum; but there will still be a second impulse on the records, due to the energy via the upper stratum. The arrival times of the two classes of impulse may be plotted and will result in defining two intersecting straight lines as shown in the diagram. The slope of these lines gives the velocities V_1 and V_2. The point of intersection C defines the distance at which the arrivals by the two paths are simultaneous. The two velocities enable us to define the angle with which the ray impinges on the surface of discontinuity. Knowing the distance to the point of intersection, the two velocities and thence the angle of incidence, we can determine the depth of the upper stratum.

It is now clear why Abbot's velocities were greater than those of Mallet. Abbot was working at greater distances (8-13 mi.) and was measuring the velocities, at depth, in a high-speed stratum. Mallet was working at distances of about a mile and was measuring the velocity in the upper slow-speed stratum.

Considerable time has been devoted to explaining this seismic method of determining the thickness of a surface layer and the velocities in upper and lower strata because it is so important and far reaching in its application. The method can be extended to more than two layers—three, four, or even more—yielding the thicknesses of the layers and the velocities in each. It can be used to determine also whether the surfaces of discontinuity are parallel to the surface or tilted and it will give the angles of tilt. It is known as the *refraction method* and will, henceforward, be referred to by that name.

In attempting to explore the entire thickness of the crust (about 25 miles) a difficulty presents itself—the explosions we can safely and economically use are inadequate to produce energy sufficient to travel to the depths and distances required. Recourse must be had to earthquakes—not severe, but well located. Such small shocks usually follow a severe earthquake and are known as *aftershocks*. Immediately after a major earthquake, portable seismographs may be rushed to the epicentral region, a timing system arranged, and continuous records made. The aftershocks will

originate not far from the original source. Several hundred, sharply-defined, will often be experienced. The data obtained yield much information as to the structure and thickness of the earth's crust *in that particular vicinity.*

Studies of this kind have been made in Japan, in central Europe, and in California. The crustal structure determined for Japan seems to be the simplest, that in California the most complex. No such studies have been made in Canada, but the data obtained from the records of the Timiskaming earthquake of 1935 show that the velocity in the outer edge of the mantle immediately under the crust is higher in Canada than in the outer edge of the mantle under Japan, central Europe or California. However, we are here considering the methods of determining earth structure, not the results obtained, so we shall pass on to the methods of probing the mantle of the earth, that spherical shell about 1800 miles thick below the crust and above the central core.

Before doing so it is necessary to note one further very necessary contribution from crustal analysis. In speaking of the methods used for locating earthquakes care was taken to say: "given a dependable time-distance graph." Science *gives* nothing gratis and yields her most valued and most valuable data only to those who seek; though sometimes, it is true, they do not know exactly for what they are looking or why they require it. One of the difficulties of obtaining a time-distance graph has been mentioned—the great areas on both land and sea unserved by seismograph stations at which to record the exact time of arrival of the elastic waves from an earthquake *for which is accurately known the epicentre, focal depth, and time of occurrence.* Even had we the optimum distribution of stations, it would still be necessary to have, for each of a series of selected earthquakes, the position of the epicentre, the focal depth, and the focal time. In other words, to locate an earthquake we must have accurate time-distance graphs and to construct such graphs we must accurately locate an earthquake or earthquakes. It appears to be an impasse; but seismology has advanced, nevertheless, by a series of approximations—applications of the method of "cut-and try."

Progress has been slow but steady over the years, as seismologists have gradually arranged for more stations, devised more

efficient seismographs, and perfected timing arrangements. We may not here enter into details. Suffice it to say that remarkably good time-distance graphs are now available—so good that it is becoming necessary to take account even of the fact that the earth is not quite spherical.

The location of epicentral position and the determination of focal depth and focal time (for earthquakes which can serve to improve the existing time-distance graphs, yielding more accurate values for focal depth which we have seen to be of so much interest) are to be accomplished only by means of seismographs concentrated over an actively seismic area. The instruments must be in place at stations situated near a prospective earthquake source and must operate continuously until a shock occurs sufficiently strong to be recorded up to great distances. The near-station data can then be used, after the manner of the refraction method previously described, yielding definite knowledge of the epicentral position, focal depth and focal time. These, with accurately timed registration at stations over the entire distance range (or as much of it as possible), will permit a new refinement of existing time-distance graphs.

A sufficient concentration of seismographs over a seismic area is found at only a few places in the world—at the present time in Japan, central Europe and California. Now, for an earthquake at any one of these places, some parts of the distance range must lie over water-covered areas where seismographs cannot be placed and also over other regions where, as yet, no stations are in operation. It is for this reason that efforts are being made by all seismologists to continue the operation of existing stations at as high an efficiency as possible and also to arrange for the inauguration of new stations at strategic points. Canadian stations are particularly valuable, as yielding data for parts of the distance range otherwise not covered, for earthquakes in Japan and California.

In order to co-operate in the attack on this major problem of seismology—the perfecting of the basic time-distance tables—a seismologist may decide to make a complete study of all records of some earthquake which appears from preliminary reports to be a promising source of fresh data. Requests are sent out to all the seismograph stations of the world asking for the loan of their

records for this particular earthquake. Such a thorough study may extend over as much as two years. Canada has made complete studies of three major earthquakes and has loaned records of many others to seismologists engaged in research. Studies of this kind are most efficient means of obtaining data for furthering our knowledge of earth structure.

Let us, then, take for granted that we have a perfected time-distance graph for the *P*-waves a normal earthquake. That is taking a great deal for granted but we already have very good graphs and we fully expect to have better ones as time goes on. The hypothetical, perfect graph tells us the rate at which the nose of the ever-widening circle of *P*-waves is radiating outward from the epicentre about the surface of the earth. That is all we ask to know. It is this we crave to apprehend better year by year.

If we knew the varying velocity with which this surface circle of energy progresses throughout the entire distance range from the epicentre to its antipodes, we should be able to deduce the rate at which the waves travel at various depths within the earth and through what surfaces of discontinuity they pass. We may speak of the nose of surface energy as the *trace* of the waves and speak of its velocity as the *trace velocity* or *apparent surface velocity* in contradistinction to the true wave velocity at any point within the earth.

The time distance graph gives the data for determining at any given distance the *trace velocity*; for we have only to find the rate at which distance varies with time at that particular distance range. For example we can take as our distance say 2500 miles. We find how long it takes the *trace* to reach a distance of 2500 miles by simply reading the ordinate of the graph for this distance. Now we read off the time it takes to go to 2600 miles. The difference in these gives the time it takes the trace to travel 100 miles at the distance 2500 miles. For those who are used to the process we simply say that the tangent to the time-distance curve at any distance value gives the *apparent surface velocity* or *trace velocity* at that distance. Suffice it to note that it may be deduced from the time-distance graph.

The most difficult part of the task set by this discussion now appears, that which the speaker so far "ain't never tried yet."

It is hoped, however, that it may prove feasible to present, without recourse to technical details a clear and *convincing* picture of just how the time-distance graph contains in its very shape the data from which may be deduced the velocity at any given depth within the mantle of the earth.

Before doing so, it is necessary to take drastic liberties with the earth. We have a time-distance curve for an earth, the crust of which varies from one point to another. We require for consideration a time-distance curve for an earth stripped of its outer crust. We may not be able to do this physically but we can use our knowledge of surface structure to cut off a little bit of distance and a little bit of time from each end of every focus-to-station path, obtaining time-distance values for that part of the earth which lies below the crust.

If you had a time-table showing the actual time it would take you to go, via subway, from Times square to the surface levels at various subway stations in New York, you would not have a fair appraisal of the various rates of travel on the subways concerned; for some subway platforms are deeper than others and some are more difficult of access. If you took off from the tabulated values the distances travelled forward in going down the steps on entry and in ascending on exit you would have new distance values in each case. If you deducted the time spent in entering and leaving you would have new time values in each case. Using these corrections to make adjustments to the original time-tables, you would have, in effect, stripped off New York to the subway level. At least you would have developed a subway level table from a surface level table.

After a procedure somewhat analogous, we may assume we now have a new and hypothetically perfected time-distance graph for an earth stripped of its crust. We know that by applying the refraction method we can obtain the time velocity just at the bottom of the crust and in the outer edge of the mantle. We assume that, throughout any part of a concentric spherical shell defined by any given radial distance from the earth's centre, the conditions are the same—the true velocities are uniform over the whole shell. Thus, the velocity deduced just below the shell is taken as uniform over the entire earth.

You will remember that it has been stated that we have recently learned that this is not so. The true velocity at the outer edge of the mantle under Timiskaming is greater than that for the outer edge of the mantle in Japan. Very well! we shall have to continue this process of stripping the earth and adjusting our time-distance curve to a still greater depth until our premised conditions *are* satisfied. It will be sufficient if it is here made plain; that we *can* use seismological methods to get a time-distance curve for an earth stripped of all lack of uniformity throughout any concentric shell; that we *can* find the trace velocity at any distance from the tangent to such a curve; and that we *can* determine the true velocity at

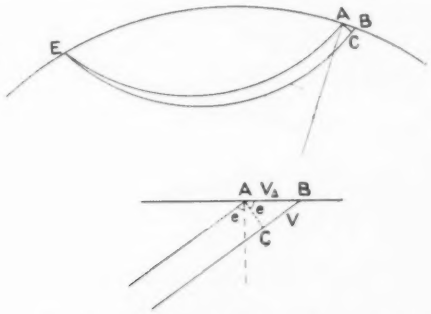

Fig. 6.—Diagram illustrating the method of deducing the angle of emergence *e* of a ray at any chosen epicentral distance *E A*.

the very surface of our stripped earth by application of the refraction method described for surface conditions. We have also, in effect, moved the origin from some point within the earth—the focus—to a point exactly in the surface of our stripped earth. Our amended time-distance graph begins at zero-zero—at the origin of co-ordinates. We may choose any point on the surface of our stripped earth and image an earthquake focus there. Proceeding to some distance about the surface of the stripped earth, we come to a point where the conditions of Fig. 6 obtain. Here two separate rays from the focus *E* emerge at the hypothetical surface of the stripped earth. It is assumed that they are chosen so that the

second ray reaches B just one second after the first ray reaches A. Thus the distance AB is a measure of the trace velocity; for it is the distance travelled by the trace in one second. We draw the line AC perpendicular to CB; thus the distance CB is a measure of the true velocity at the surface; for it is the distance travelled by the wave along the ray CB in one second. Now if we know the sides AB and CB of a right-angled triangle we can measure the angle of emergence, e, which is equal to angle CAB. We know

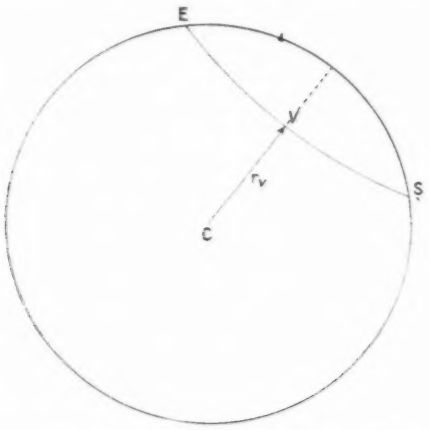

Fig. 7.—The Herglotz-Wiechert method applied for any chosen epicentral distance $E\,S$ yields the value of the vertex radius r_v and the true velocity of the earthquake waves V at that depth.

the trace velocity from the amended graph and the true velocity from the refraction method so we can in this way find the angle of emergence of the rays at all distances, provided they do not dip into the core and become deflected. Up to more than half the distance around the earth from the epicentre chosen, *we can deduce the angle of emergence of the rays.*

As we saw in the refraction method, a ray passing from a stratum of lower velocity to one of higher velocity is bent toward the surface.

If the true velocity increases at successively-deeper levels the ray will be bent more and more until it is at right angles to the radius. This is its deepest point. It then traverses the second half of its path which is the mirror image of the first half; and it emerges at the surface (of the stripped earth let us remember) at the same angle of emergence with which it started. That is to say, the ray is symmetrical about its centre radius through the vertex (see Fig. 7).

Clearly the amount of bending to which the ray is subjected is the sum of all the effects within its path; and the angle of emergence of the ray at any given distance is determined by the velocity at

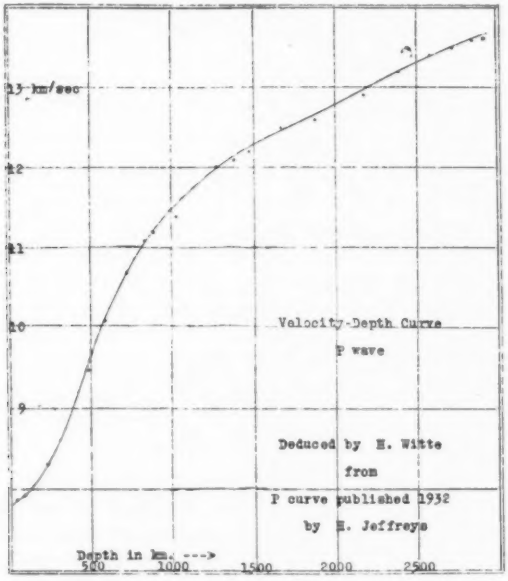

Fig. 8.—Velocity-depth curve by Witte, 1932, based on Jeffreys' *P* curve.

every depth through which the ray passed. If we could set up a mathematical expression giving the value of the radius to the vertex E_v and the velocity V at that vertex, of any chosen ray defined by its epicentral distance of emergence in terms of the emergence angle

for that epicentral distance, we could get one value of a true velocity at a known depth. For, as we have seen, we *can* determine emergence angles at every epicentral distance on the stripped earth. That, very briefly, is exactly what has been done. It is known as the Herglotz-Wiechert method.

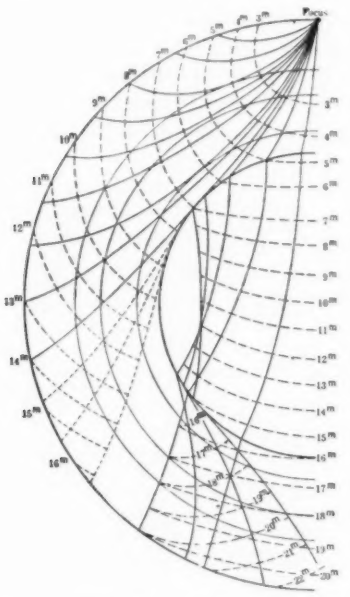

Fig. 9.—Cross section of the earth showing rays and wave fronts of earthquake waves and the "blind zone." The last direct *P*-wave to emerge at the surface is the one grazing the core whose wave front is marked 14m indicating that the transmission time from the focus to this point is 14 minutes.

Applying the Herglotz-Wiechert method once, we get one depth and the one corresponding true velocity. Applying it repeatedly, we get other depths and their corresponding velocities and thus bit by bit we get the complete graph which shows the variation of velocity with depth at all distances, *down to the core*. The velocity depth curve deduced by Witte in 1932 is reproduced in Fig. 8.

Down to the core, why no farther? Because the ray which barely grazes the core is the last direct *P*-wave to reach the surface. All others are deflected into the core in such a way that, beyond a certain distance range, no direct ray emerges at the surface. There exists a "blind zone" as shown in Fig. 9. No single part of the earth structure defined by seismology is quite so certain as the presence of the core. The blind zone is very clearly demarcated. It is possible to read off directly from a velocity-depth curve, such as that of Fig. 8, the depth to the core. The fact that the blind zone begins abruptly shows the surface of discontinuity to be sharply defined.

If a mathematician be given the dimensions of the earth, the structure of the crust, the variation of velocity in the mantle, and the depth to the core, he can compute the time it should take various waves, reflected within the earth, to reach the surface and the seismograms may be searched to see if they confirm the work which gave us the velocity-depth curve. Not only the reflected *P*-waves but the *S*-waves of which we have nearly forgotten; for, as we got a velocity-depth curve for the *P*-waves, so we can get one for the *S*-waves. Furthermore, when an elastic wave *either* of *P* or *S* type is reflected or refracted it generates other waves of *both* types. Thus we may have a *P*-wave reflected at the under side of the surface as an *S*-wave and so on. The number of such possible, complex wave paths is very great and the times once computed may, as we have said, be checked on seismograms. Some of the possible paths are shown in Fig. 10.

So, step by step, by cut-and-try, by modification of theory and data, we have the means of probing the earth not only in the crust but in the mantle down to a depth of about 1800 miles. But we stand at the barrier—the margin of a core of radius 2200 miles. What can we learn about the core?

We can learn something of the nature of the material in the crust and mantle by knowing the velocity with which earthquake waves traverse them. We know from gravity measurements the total mass of the earth. The mantle and crust do not nearly make up their share of mass per volume (density). The core must be very heavy; the density must be great. We can deduce the approximate average density of the core. If we had a time-distance

curve for the core and knew the true velocity just inside its boundary, we could apply the Herglotz-Wiechert method again to an earth stripped to the core and find a velocity-depth curve for that greater depth. So far no means has been found to do this. We know the total time for a wave such as that shown in Fig. 11 to reach the surface. We can compute the time required for the sections outside the core and we can find the end points of these

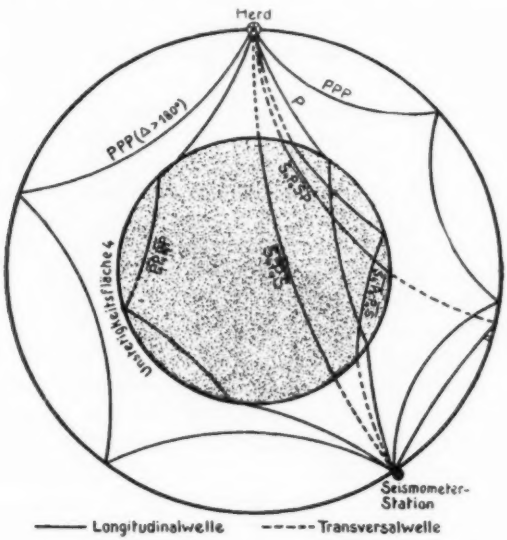

Fig. 10.—Some typical complex earthquake rays from the focus (herd). The subscript 4 indicates the passage of the so-called fourth surface of discontinuity within the earth (Unstetigkeitsfläche 4), which marks the boundary of the core.

branches at the core boundary. We know thus the time required for a wave to traverse the core along a path which has its end points fixed. But, not knowing the variation of velocity with depth in the core, we cannot say what shape the path has therein.

However, to make a long story short, there are, as we have

partly indicated, a certain number of conditions which must be met if an assumed variation of velocity with depth within the core can be true. Over twenty such variations have been assumed by Gutenberg, checked with end data, and the most probable one selected. The research continues. We have still much to learn about the core.

Returning to the surface, let us see how we may use seismographs to probe the outer layers of the crust to depths which the drill may reach and confirm. We may use the refraction method

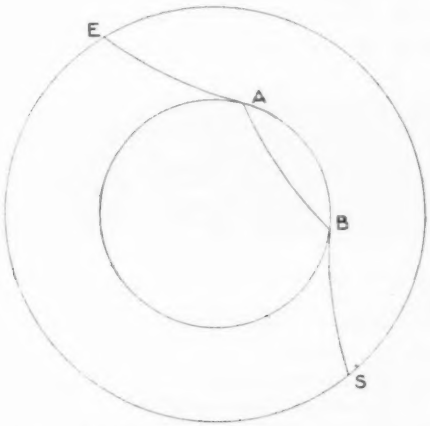

Fig. 11.—Path of PKP-ray, sometimes designated $P_4\,P_4\,P$ or $P_c\,P_c\,P$.

which was described; and indeed it was used to excellent effect up to about 1929, when researches in radio made possible a new method which is now so useful that, in the United States alone, more than a million dollars a month are being spent in applying it to probe the upper earth strata in search of oil.

It is known as the *reflection* method. A shock generated from the explosion of from a quarter to a half pound of dynamite is recorded on a series of seismographs placed a measured number of feet apart at a measured distance from the blast. A very common "spread" is to have six seismographs at intervals of fifty feet with

a thousand feet from the nearest seismograph to the shot point. The shot is buried in a hole drilled, usually, fifty feet deep; and the recording is done on very rapidly moving paper with time marks each tenth of a second. Time fails here to do more than say that this method uses electrical seismographs which feed their impulses through wave filters and amplifiers so that the direct ground motion is killed out and those waves enhanced which have been reflected

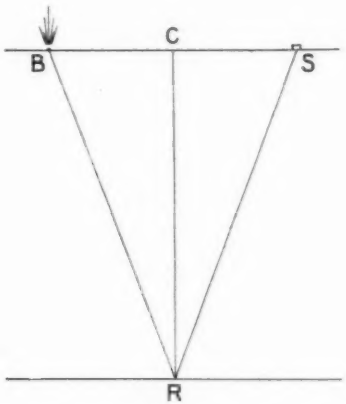

Fig. 12.—Ray from blast to seismograph. The average velocity from the reflecting layer at *R* to the surface is found from shots fired in dry wells in the region, or by refraction shooting. The elapsed time shot to seismograph is known. Hence the distance *BRS* is known. The distance *BS* is measured. Hence the depth *CR* may be calculated.

from a selected sub-surface stratum which is thought to have oil-bearing possibilities.

The average velocity within the upper strata above the reflecting layer being studied can be measured by the refraction method or, where dry wells exist in the area, by measuring "up-hole time" from a shot in the well. Knowing the average speed and the elapsed time, and the distance from shot to seismograph, we have sufficient data to solve the conditions shown in Fig. 12 and learn the depth to the reflecting surface.

The crews work over the networks of country roads, finding the depth from point to point to the selected layer or "horizon" within the earth, until they find some place where it up-bulges about the same way as a large carpet would up-bulge if you were to put an inverted soup plate in its centre. Imagine a carpeted dining room with a table on the centre of the carpet and with an inverted plate under the carpet and under the table. The table top represents the earth's surface—the carpet represents the oil-bearing reflecting layer. The geophysicist seeks the invisible, up-bulged part represented by that hump in the carpet pushed up by the inverted plate. In practice, the layer may be at any depth up to a couple of miles. The bulge may be only fifty feet above

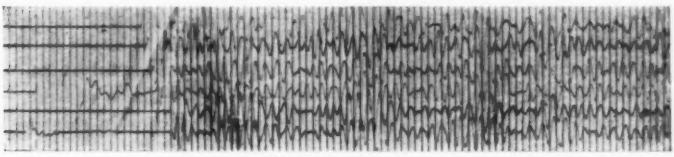

Fig. 16.—Section of a typical six instrument seismogram.

the general level of the layer. But if such a bulge exists in those invisible depths, to learn of it is worth money; for that is where the oil will be—if there is any.

Figures 13-15 show reproductions from photographs taken in the field and Fig. 16 shows a typical record. To deal adequately with this subject would take a whole series of lectures, for it is a very live business; and new technique and new discoveries are being reported every month. Some idea of the magnitude of the business may be given when it is stated that more than 200 seismograph crews are working in the United States alone, and that it costs at least $30,000 to equip a crew and $3500 a month to run it. Crews with equipment may be hired at an inclusive charge of $9000 per month. No companies are organized for this work in Canada, but some United States companies and also some from Germany have operated here.

It has been a long story, with many very summary and sketchy flights over details. We have seen how seismology penetrates to

depths of a mile or two so quickly and surveys wide areas so rapidly that the expensive wielding of pick or drill need not be resorted to without some reasonable hope of reward. Aftershocks permit the extension of such methods to the bottom of the crust, which we have found to be of varying stability, varying thickness, and varying structure. The work on the crust permits us to arrive at a time-distance curve for an hypothetically stripped earth, after which the Herglotz-Wiechert method enables us to obtain a velocity-depth curve for the mantle. With these data at hand, we may compute the arrival times for various complex waves which should record at the surface, thus checking the previous deductions. We know some things about the core but it still remains to a large extent an unsolved problem—by no means the only one in seismology of course.

So, step by step, year by year, slow but steady progress is being made, by co-operative international effort, toward a more accurate knowledge of earth structure. This is one of the main reasons for studying earthquakes, whether in a seismic region or in relatively-quiescent Canada.

Department of Mines and Resources
Ottawa, Canada,
March 25, 1938

THE CENTENNIAL CELEBRATION OF THE LOOMIS OBSERVATORY

By HELEN SAWYER HOGG

THE year 1938 sees the completion of one hundred years of existence of the second oldest extant observatory on the North American continent—the Loomis Observatory of Western Reserve Academy at Hudson, Ohio. Elias Loomis, a graduate of Yale in the class of 1830, was elected Professor of Mathematics and Natural Philosophy at Western Reserve College in 1836. He was sent to

Fig. 1. Elias Loomis (1811-1889) taken shortly after he was a professor at Western Reserve College, 1836-1844.

Europe to purchase instruments and books, and upon his return, supervised the construction of the observatory. The instruments were mounted and put into use in September, 1838. The early history of this observatory and the story of its origin parallel closely the founding of the Hopkins Observatory of Williams

College, which is the oldest extant astronomical observatory on this continent. The reader who is interested in following the histories of the earliest observatories in North America is referred to the excellent and comprehensive article "Early American Observatories" by Prof. Willis I. Milham of Williams College, which is published in both pamphlet and book form.

In the past hundred years, the original Western Reserve College

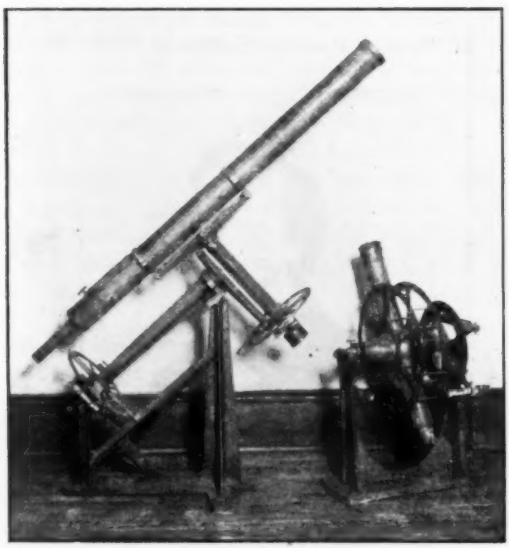

Fig. 2. The telescopes, a 4-inch equatorial and a 4-inch transit, brought back from England by Loomis in 1837.

has divided into two parts. The early buildings and the original site, including the Loomis Observatory, are now Western Reserve Academy, a preparatory school for boys, at Hudson. Some twenty miles to the north, in the city of Cleveland, is now located Western Reserve University, the larger and more advanced institution.

To celebrate the centennial, invitations to visit the Academy on May 7th and 8th were extended to a number of astronomers

from nearby territory, and an admirable astronomical programme was planned. The first of May finds the campus at an exceedingly beautiful season with the rows of stately old elms in young leaf. The Observatory had been especially renovated for the occasion. The two instruments procured by Loomis in England, namely the Troughton and Simms equatorial telescope, with an aperture of four inches, and the transit instrument, with an aperture of three inches, have not been on their original mountings constantly during the past hundred years. But the instruments have now been remounted, and the observatory restored as far as possible to its original condition by Mr. R. H. Cleminshaw of the Academy faculty.

Several dozen astronomers came from all directions. Canadian astronomy was represented by Dr. J. S. Plaskett, Prof. Chant, and the writer, who enjoyed a beautiful motor trip to the meetings through the kindness of Prof. and Mrs. Chant. A detailed account of the celebration and the papers presented are to be published in *Popular Astronomy*, but the event is deemed worthy of recording for JOURNAL readers also.

An astronomical seminar was planned for Saturday afternoon at two o'clock, with three important guest speakers. The seminar was held in the fine arts building of the academy—a cheese factory a hundred years ago, now converted into a beautiful, well-decorated building. Here about seventy-five scientists listened to Prof. Otto Struve of Yerkes discuss the various physical factors which account for the widths of absorption lines,—damping, Stark effect, dilution, rotation, etc. Prof. Dean McLaughlin of Ann Arbor continued the discussion with remarks on the Be stars, whose spectra vary in a variety of ways. Prof. Donald Menzel of Harvard then concluded the afternoon programme with a summary of various theoretical problems of stellar spectra. The scientists were graciously invited to tea at the home of the headmaster, Dr. Joel Hayden, after which about four hundred and fifty boys, parents, and scientists gathered for dinner in Cutler Hall. Following the dinner, Dr. Shapley gave the address of the day on "Sidereal Organizations",—a popular address, since the audience was mostly non-astronomical, but with various choice tidbits of recent astronomical advances thrown in for the benefit of the professional

astronomers present. At the close of Dr. Shapley's lecture, Dr. Curtis showed the beautiful and valuable moving pictures of solar prominences obtained at the McMath-Hulburt Observatory of the University of Michigan.

The Sunday morning service was held in the century-old chapel, extremely beautiful in its simplicity, with a white interior decorated by two large urns of pink hawthorne. Prof. Milham brought the greetings of Williams College and the Hopkins Observatory, and

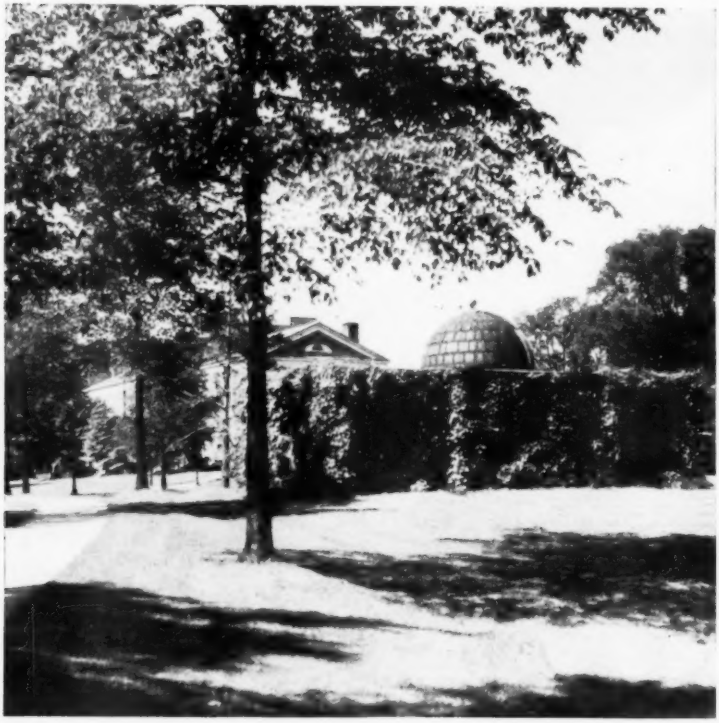

Fig. 3. The Loomis observatory of Western Reserve Academy, completed in 1838, and the second oldest extant observatory on the North American continent.

read a quotation from the Journal of the New England poet, Ralph Waldo Emerson, which cannot fail to appeal to all students of astronomy.

> Of all tools, an observatory is the most sublime. . . . What is so good in a college as an observatory? The sublime attaches to the door and to the first stair you ascend; that this is the road to the stars. Every fixture and instrument in the building, every nail and pin, has a direct reference to the Milky Way, the fixed stars, and the nebulae, and we leave Massachusetts and the Americas and history outside at the door when we come in.

Prof. Mountcastle of the Physics department of the Case School of Applied Science at Cleveland brought the greetings of that institution. The address of the morning was delivered by Dr. Dayton Miller, also of the Case School, on "The Spirit of Science and the World of To-day." It was full of worth while thoughts for the scientists present as well as for the laymen. One quotation from the library of the city of Rochester seemed particularly noteworthy:

> The shadows will be behind you
> If you walk into the light.

The formal celebrations ended Sunday noon, with dinner in Cutler Hall, after which the astronomers dispersed, having enjoyed an instructive and delightful week-end.

David Dunlap Observatory,
Richmond Hill, Ontario.

METEOR NEWS

Observations relating to meteors and meteorites are cordially invited.

The Origin of Meteoric Material

One of the greatest problems in the study of meteors and meteorites has been to account for the existence and nature of the meteoric material throughout space, of which meteorites have generally been considered as representative samples. The scope of the problem has been greatly expanded by recent and apparently conclusive evidence that a large percentage of meteors visible in our atmosphere arrive from interstellar space well beyond the confines of the solar system. The discussion, therefore, cannot be localized as one concerning the solar system only but must be considered at least from the standpoint of our own galaxy. Since no theory yet suggested has fully met the test of our present knowledge any new paper on the subject is of definite interest.

In this connection I would like to call attention to a recent paper[1] by Axel Corlin of the Lund Observatory. In this article Dr. Corlin first points out some of the objections to the previous theories of the origin of meteoric matter. With respect to the view that meteorites have been thrown off from planets by volcanic action or other means he computes the braking effect of a planetary atmosphere and shows that for small objects the initial velocities would have to be unreasonably large to escape from the planet's gravitational attraction. (Even an object of 20 tons would have to have an initial velocity of over 30 miles a second to escape from the earth through its atmosphere. Minimum velocities for smaller masses become extremely high.) If small planets lacking an atmosphere are considered as the origin of meteoric material then, after escaping from the attraction of the planet, this material would still have to be moving fast enough to escape the gravitational field of any star about which the planet was revolving. The frequency of suitable planets with the attendant volcanic action would have to be unreasonably great to supply the observed amount

[1]How larger bodies may be built up out of small particles in interstellar space,—by Axel Corlin, Zeit. f. Astrophysik, vol. 15, p. 239, 1938.

of meteoric material. A similar objection applies if planets are considered to explode and scatter their debris in space (an event which seems of doubtful possibility in any case). Dr. Corlin sees another objection to the planetary theory in that the internal structure of meteorites is in the main very dissimilar to terrestrial minerals. He suggests that it is more logical to assume that small particles of interstellar matter of various sizes combine to form larger solid objects as suggested by Arrhenius in 1917 and by others. The means by which this might take place are now investigated. Mechanical collisions will not be very frequent and will also tend to pulverize material. Gravitational attraction might play a part but on logical assumptions it is found that approximately 10^{15} years will be required to double a mass. This is far too long as the ages of meteorites have been found to be about 10^9 years. An agency which Dr. Corlin considers more likely is the attractive force of an electrostatic charge. One of the natural phenomena recently recognized by physicists is that of cosmic ray bursts. A primary cosmic ray striking an object may, through secondary action, release instantaneously hundreds or even thousands of negative electrons, thus leaving the body with a positive charge. It is computed that a particle in space of radius $r=1$ cm will be struck by a cosmic ray producing a burst once every 133 hours and that the resulting positive charge (assumed 500 electron units on the average) will remain for 37 hours before leaking entirely away. Thus, such an object is charged for nearly a third of the time. For smaller objects the charge will remain for a longer time, varying as $1/\sqrt{r}$, but the frequency of bursts will decrease as r^2, resulting in a generally neutral condition for small particles. Objects with r greater than 2.3 cm remain permanently charged. It is pointed out that, while a body is charged, it will tend to attract neutral or oppositely charged particles and it is assumed that the building up process resulting from this has been operative in the formation of meteoric masses of various sizes. Since the electrostatic charge is near its maximum for a short time only after each burst the accumulation of mass will vary as the frequency of the bursts, that is as the surface area or as r^2.

Paneth, by a study of helium-lead content in samples about 10 gm in weight, found an approximate age for meteorites of 10^9 years. If it is supposed that a mass of 10 gm is built up to one of 10^5 gm in

10^9 years it is found that on the average a meteoric particle must accumulate 1.6×10^{-8} gm of matter for each cosmic ray burst received. The largest condrules found in meteorites are of about the same size, 4 to 6 cm diameter, as the computed size of the smallest interstellar particle remaining constantly charged, and it is natural that bodies larger than this would not attract each other as they would be similarly charged and thus repel. In other words, any object larger than about 5 cm diameter would be expected to pick up only particles smaller than this size. Accumulating mass at the above rate 1 gm would grow to a mass comparable to some of the larger comets (about 6×10^{15} gm) in a period of 4×10^{12} years.

It is admitted that Jung is correct in his conclusion that interstellar particles will in general be positively charged through the photoelectric effect of starlight but it is contended that this applies to average conditions throughout our galaxy and that in certain localities the ratio of ionizing quanta to free electrons may be considerably lower than the average and that here attractive forces due to electrostatic charge will be effective. The above remarks summarize the chief points in Dr. Corlin's paper.

In commenting on this publication I would say at the outset that the arguement that attractive forces arise through the impact of cosmic rays seems well founded. For the theory to be convincing, however, it would seem that more attention should be paid to computing the probable size and effectiveness of these forces resulting from electrostatic charge, as upon this point rests the whole validity of the suggestion. This is not taken up in the paper as the constant for the accumulation of mass is derived directly from the assumption that 10 gm increases to 10^5 gm in 10^9 years. The nearest approach to a discussion of the sufficiency of the electrostatic forces to effect material accumulation of mass is in the computation of the average mass to be picked up per cosmic ray burst.

Now, if we assume with Corlin that an average burst delivers a charge of 500 electron units then two spheres 1 cm in radius, of specific gravity 5, and oppositely charged by the above amount, will attract each other with a force of $\frac{12\times10^{-5}}{d^2}$ dynes, d being the distance between them. The gravitational attraction between the same objects

will be about $\frac{3\times10^{-5}}{d^2}$ dynes. But in comparing the two types of force it must be remembered that the full electrostatic force is operative for only a very small fraction of the time and that oppositely charged bodies will interact relatively rarely. The chief type of electrostatic attraction to be considered is that between positively charged masses and neutral ones, where the forces are very much smaller except when the distances between the masses are of the same order of magnitude as their diameters. One should also make some approximation of the limits within which capture is possible, assuming probable relative velocities for the interstellar matter and remembering that the electrostatic attractive forces will virtually vanish at the first contact of two particles and will not be operative in holding them together after they have once touched. The above would indicate that the general effect of the electrostatic forces cannot be much greater than, if as great as, the gravitational forces but a final decision will have to rest upon detailed theoretical work.

The difficulties in the way of considering meteorites as fragments of larger masses are certainly appreciable and should not be underestimated and yet authorities, such as Farrington for example,[2] who have exhaustively studied meteorite structure, definitely conclude that this structure is consistent only with the meteorite's previous existence as part of a larger mass. Merrill considers the tuffaceous (or volcanic) origin of a large group of meteorites as beyond question.[3] He has also shown[4] that the chondrules, the approximately spherical inclusions which are the most characteristic feature of stony meteorites, divide naturally into two groups. First, those whose internal crystalline structure is consistent with their having once been like drops of fiery rain in a fusing atmosphere. These occur in the group of meteorites most clearly tuffaceous in origin. Second, those of a more compound internal structure, many showing marked evidence of being shaped to the spherical form by mechanical attrition.

[2]Meteorites,—by O. C. Farrington, p. 211, 1915.

[3]Composition and Structure of Meteorites,—by G. P. Merrill, U.S. Nat. Museum Bul. 149, 1930.

[4]On Chondrules and Chondritic Structure in Meteorites,—by G. P. Merrill, Proc. Nat. Aca. Sci., vol. 6, p. 449, 1920.

Certainly the first type and probably the second also can most easily be accounted for by assuming origin on a larger mass. This same theory of origin is also supported by the presence of large iron meteorites as they are quite consistent in composition with the probable nature of planetary interiors but it would seem difficult to assume that these meteorites were built up gradually in space, picking up only iron and nickel particles to the exclusion of other elements. The fact that meteorites differ somewhat in mineral composition from terrestrial rocks does not necessarily mean that they could not have been formed on a planetary or asteroidal object. Prior, Merrill, and others have pointed out that the chief general differences between terrestrial rocks and meteorites indicate that the latter were formed in a non-oxidizing atmosphere. This is quite consistent with recent investigations which seem to show that an atmosphere containing free oxygen is the exception rather than the rule. There is no reason to suppose that the apparent gap in numbers of known objects between the largest meteorite and the smallest asteroid is other than observational and yet there is difficulty in accounting for the masses of even the large meteorites on the building up hypothesis unless we assume a very long time scale.

In conclusion it may be added that as yet it is unsafe to consider the high percentage of interstellar velocities found for visual and telescopic meteors as applying to meteorites as a class and also that there is yet no very clear demonstration of any close connection between the cometary meteor showers and the small samples of matter which have fallen to the surface of the earth from space. Whatever the successful explanation of the origin of the latter turns out to be it must take into full account both mineralogical structure and astronomical theory.

P. M. M.

REVIEW OF PUBLICATIONS

Spectral Atlas of Bright Stars of the Northern and Southern Hemisphere, by Josef Klepesta, pp. 28, 10 x 14 inches, Prague, 1937. (Order from Dr. Hubert Slouka, 1478 Nad Klikovkou XVI, Czechoslovakia. Price $2.50, postpaid.)

With the ever-increasing importance of the spectrographic study of the stars the spectral type of a star is of at least equal interest with its apparent magnitude and yet, in the past, no atlas has been published which shows at a glance the spectral type of even the brighter stars. Thanks to Dr. Klepesta such an atlas is now available and it should prove extremely useful to many professional as well as amateur astronomers. All stars brighter than visual magnitude 5.1, as given in Schlesinger's Catalogue of Bright Stars, are included. Five maps, 11 by 15½ inches, cover the celestial sphere. Three equatorial maps extend from –45° to +45° Dec. and include $8^h\ 40^m$ in R.A. The two remaining maps show the circumpolar stars north and south. Whole magnitudes are indicated by the size of the dots representing the stars, these ranging in diameter from 1 mm for 5th magnitude stars to 7 mm for Sirius. The main spectral class is represented by the colour of the dot, a seven colour printing process being used for all the maps. Classes O and B are violet, A blue, F green, G orange, K pink, M and N red, while all other material on the maps is printed in black. The position in the spectral class, following the classification of the HD catalogue, is indicated by a numeral printed beside each star. For example, a second magnitude A5 star is represented by a blue dot just under 4 mm in diameter with a small numeral 5 beside it. The names of the brightest stars and the Greek letter designations are also given on the maps. The principal stars in each constellation have been joined by straight lines but no coordinate lines have been drawn on the body of the maps as high accuracy for the star positions cannot be claimed owing to the difficulty of alignment in seven colour printing. (Considering these difficulties, however, the printing seems to have been carried out remarkably well.) Coordinates are indicated around the edges of the

maps in such a way that anyone who so wishes can easily draw in the coordinate lines. Their omission makes the stellar groupings stand out with less confusion and seems a good idea but there is no very evident reason for omitting the magnitude scale which, if printed with each map, would materially assist in the use of the atlas.

There is a brief introduction in English which describes the chief characteristics of the spectral classes. The atlas also includes good half-tone reproductions of 28 representative spectra taken at Ann Arbor, Michigan, which illustrate the entire range of the spectral sequence. The binding is an attractive star design in blue with stiff board covers, cloth backed. The writer would recommend this atlas as a distinct aid to anyone interested in the physical study of stars visible to the naked eye.

P. M. M.

The Nature of Variable Stars, by Paul W. Merrill. 134 pages, 5¼ x 8 ins., 2 plates and 12 text-figures. N.Y. and Toronto, Macmillan, 1938. Price $2.25.

This is an excellent work. The author has been on the staff of Mount Wilson Observatory since 1919, is thoroughly familiar with his subject and writes in a clear, interesting and sometimes picturesque style. The book contains much originality in treatment and is full of late information. It will be found pleasing and profitable both by the layman and the professional.

There are eight chapters: (1) The nature of stars in general, (2) Varieties of variable stars, (3) Discovery and cataloguing, (4) Light curves, (5) Physical properties, (6) New or temporary stars, (7) Motions, (8) Variable stars and the stellar system.

The book shows well how the physicist, the chemist and the astronomer co-operate in their researches. "We cannot expect," says the author, "ever to travel to the stars or to make them do our bidding, but we may hope to learn from them phases of truth about matter, electricity, light, and gravitation which will profoundly benefit the human race." Some variable stars (*e.g.*, Mira) are enveloped in a voluminous literature. In such cases our author makes brief quotations from the original publications and elucidates them with judicious foot-notes when necessary. His pictures of novae and

super-novae are lively as well as accurate, while his outline of modern theories—especially of long-period variables suggests how much we have yet to learn.

Dr. Merrill does not give detailed instructions for the practical observer but such are readily available. His admirable outline of the whole subject will undoubtedly lead to the enlistment of others in this fascinating branch of astronomy, in which the services of amateurs are almost indispensable.

C. A. C.

A Hundred Years of Astronomy, by Reginald L. Waterfield. 526 pages, 5¼ x 8½ ins. London, Duckworth; N.Y., Macmillan. 1938. Price 21 *s.*

The author of such a work should have a profound understanding of astronomy, and to possess that in these days requires high attainments in mathematics, physics and chemistry. In addition he must be able to organize his knowledge and present it in clear language. Dr. Waterfield seems to fulfil all these conditions and the result is a very readable and useful book. As he remarks, the present-day general reader is not satisfied with a statement of the results of scientific investigations; he wishes to understand, if possible, the manner in which the results are obtained, and in this book an attempt is made to supply that desire.

The author is an English amateur, a member of the council of the R.A.S. and the director of the *Mars* section of the B.A.A.S.

The first five chapters are preliminary. They deal with the measurement of stellar distances, the discovery of Neptune, variable stars, the sun's distance, celestial photography, telescope construction, novae and stellar brightness. The other twenty-five chapters discuss in detail portions of these subjects. For instance, chapter 12 deals with the white dwarfs and the interior of a star, chapter 18 with the absorption of light in space and chapter 26 with planetary atmospheres. After this follow a bibliography, a chronological table and indexes.

One may open the book at almost any page and find interesting matter. For example, on pages 78-9 is the story of the "Crossley Reflector" and the advent of the amateur's telescope, while on page 174 is the account of observations with the 20-foot interferometer at

Mount Wilson, with Dr. Pease's startling success after months of tribulation. Indeed the book is a mine of information.

C. A. C.

Leben und Wirken des Johannes Müller von Königsberg genannt Regiomontanus, by Ernst Zinner. 294 pages, 6½ x 10 ins.; 46 plates. München, Beck'sche Verlagsbuchhandlung, 1938.

This is number 31 in a series of volumes on Bavarian National History prepared by a commission of the Bavarian Academy of Sciences, and the author is the director of the Remeis Observatory at Bamberg in Bavaria. He is also author of *Die Geschichte der Sternkunde* (1931) and other volumes which exhibit careful research and scholarship.

Johannes Müller was born on June 6, 1436, in Königsberg and died in Rome at the early age of 40 after a life of great productivity. The name Regiomontanus by which he is ordinarily known is the latinized form of his birthplace. The present volume gives a full account of his life.

There are 14 chapters (some with several sub-sections) which deal with his infancy, his relatives, his apprentice-years in Leipzig and Vienna, his travels in Italy and Hungary, his life-work in science and in the publication of noted books in Nuremberg (53 pages), his death in Rome, the property he left behind, his portraits, and the judgment of posterity. Then follows an annotated list of the publications of Regiomontanus. The 91 illustrations in the plates at the end of the book include facsimiles of pages of his works and pictures of sundials and other instruments.

C. A. C.

NOTES AND QUERIES

Communications are invited, especially from amateurs. The Editor will try to secure answers to queries.

Congratulations

To Miss Edna M. Fuller, B.A., Secretary-Librarian of the David Dunlap Observatory, who received the degree of Bachelor of Library Science at the University of Toronto Convocation, June 9, 1938.

Two Fine Inscriptions at Rochester, N.Y.

The two inscriptions which follow were recently brought to the attention of the present writer:

At the Entrance to the University Library

Here is the history of human ignorance
Error, Superstition, Folly, War and Waste
Recorded by human intelligence for the
Admonition of wiser ages still to come.

Here is the history of man's hunger for
Truth, Goodness and Beauty
Leading him slowly on through
Flesh to Spirit from bondage to freedom
From War to Peace.

—*John R. Slater.*

At the Entrance to the Public Library

The shadows will be behind you
If you walk into the light.

How Many Pleiades Can You See?

In *Popular Astronomy* for June-July, 1938, E. P. Martz Jr. gives a sketch of the life of W. H. Pickering (Feb. 15, 1858—Jan. 16, 1938) which is full of interesting details. He states that Pickering with the naked eye could locate thirteen stars in the Pleiades cluster, while Percival Lowell said he could detect sixteen.

The Great Aurora of January 25-26; its Audibility

In the March issue of this Journal, p. 157, is some information regarding the above auroral display, including a statement regarding sounds heard at the time. In *Nature* for May 28 is an interesting paper giving measurements of its height and further evidence regard-

ing sounds heard during its appearance, by Professor Carl Störmer of Oslo, the distinguished investigator of the aurora. Professor Störmer has nine photographic aurora-stations in southern Norway and at them, during the night of January 25-26, about 1,390 photographs were taken, of which about 710 were successful. Preliminary measurements of heights are given and they range from 95 to 700 km. A fine photograph of the display seen to the south of Oslo, with the constellation Orion in the background, was taken at 9.40 p.m. G.M.T. and is reproduced in the paper. Near the horizon was a persistent green arc and above it were red rays or streamers. Soon after 9.40 a fine corona developed and the auroral activity reached its maximum. During this time Mr. Tjönn at the station on Njuke Mountain in Tuddal reports that he heard sounds. In a letter to Professor Störmer he says:

> During the imposing display of this big corona, where the whole heavens was like an ocean of flames, my assistant and I heard a curious sound which came from above, first from the south-west, then from the zenith and at last from the north-east. The sound lasted about ten minutes, rose to a maximum and fell down again, following the intensity of the aurora. I had the impression that it had something to do with the white rays. At that time I had taken off the earphones from my ears (when I had them on, I heard nothing of this sound) and went some steps aside to hear it better; that the sound came from the telephone is quite excluded. The sound is difficult to describe, it was similar to the sound from burning grass and spray. On the mountain it was absolutely quiet, no sound coming from wind, waterfalls, telegraph lines or motors. But my assistant and I heard it and are quite convinced that the sound was real. On the summit of the mountain where we had our station, only a few fir trees grow. Under us on all sides we had the forest.

Professor Störmer continues:

> The same sound was heard independently of Mr. Tjönn, down in the valley Tuddal, by Oystein Reisjaa, who in a letter has confirmed in all details the description given by Mr. Tjönn. When Mr. Tjönn heard the sound he telephoned to me; but I was so occupied by securing height determinations of the big corona that I did not pay sufficient attention to his call. On account of the great height of the aurora, it is clear that the sound could not come from the aurora itself, but from lower parts of the atmosphere; but where its origin was future observations may decide.

To the present writer the above seems the strongest evidence that sound sometimes accompanies the aurora which has been recorded.

C. A. C.

MEETINGS OF THE SOCIETY

AT TORONTO

March 22, 1938.—The regular meeting was held in the McLennan Laboratory University of Toronto, at 8.00 p.m. Mr. E. J. A. Kennedy was in the Chair. The librarian's report was read by Miss E. M. Budd, and was received. Mr. William B. Moore, 86 Broadway Avenue, Apt. 12, Toronto, was elected a member of the Society.

The paper of the evening entitled "How do they know?" was given by Dr. D. W. Best. The address was a survey of the principles and typical methods used in obtaining assured results in the older astronomy, with a briefer account of the processes which have led to recent progress in astrophysics and cosmography. In the discussion which followed, Mr. J. R. Collins, Dr. J. F. Heard, and Mr. M. W. Duncalfe took part.

Dr. J. F. Heard continued his elementary course with a lecture on "Variable Stars". He discussed periodic and non-periodic variables, the former comprising eclipsing binaries, cluster type, cepheid and long-period variables; the latter including irregular variables and novae.

D. W. BEST, *Recorder.*

AT VANCOUVER

April 12, 1938.—The 55th regular meeting of the Vancouver Centre was held in Room 200, Science Building, University of British Columbia at 8.15 p.m. on Tuesday, April 12, 1938.

Mr. H. P. Newton, immediate past president, then gave a lecture on the planets Jupiter and Saturn. The speaker purposely avoided the extensive use of material on these planets usually found in descriptive texts, and in its place gave much information that he had acquired as a result of his own telescopic observations, extending over a considerable period of time. This applied especially to information about the markings and rotation of Jupiter, and its satellites. It was shown from the evidence of photographs taken with light of varying wavelengths that the Great Red Spot has a spiral twist, suggesting that it may be of cyclonic nature. This theory is supported by the manner in which the south equatorial disturbance is observed to pass it. The atmosphere of Jupiter was said to be composed largely of ammonia and methane. It was pointed out that mathematical considerations based on the rate of rotation of the major axes of the orbits of Jupiter's satellites lead to the conclusion that the oblateness of Jupiter's appearance is due to the distribution of fluid material in its upper levels, and that this covers a solid core, approximately spherical in shape. The speaker then referred to the problem of explaining the variations in the apparent brightness of Jupiter's satellites.

As many of Mr. Newton's remarks concerning Jupiter applied also to Saturn, he was able to deal with that planet much more briefly. He pointed out the significance of the discovery (by means of the Doppler Effect) that the inner edges of Saturn's rings travel faster than the outer ones, and stated the first-discovered retrograde satellite was one of Saturn's.

Dr. E. O. Anderson, of the Department of Physics of the University of British Columbia then addressed the Centre on the subject "Stellar Diameters". He introduced the subject by showing that the size of star spots on a photographic plate are not a true indication of stellar diameters, as they are diffraction patterns, depending on the nature of the lens used. Formulae for the diameter of this pattern in terms of the wavelength of the light, the focal length and the aperture of the lens and the angular diameter of the star were used to arrive at the ratio of the diameter of the diffraction pattern to the diameter of the actual image. It was shown that this ratio would change with the stellar angular diameters in such a way as to result in similar spots for stars of various sizes. The effect of plate halations, and the "wandering" of stars due to local atmospheric refraction was also mentioned.

The speaker then reviewed the experimental data connected with Young's method of obtaining interference fringes with a double slit, and explained the elementary theory of this phenomenon. The method of obtaining a double slit by using a suitable slitted diaphragm on the objective of a telescope was described, and it was shown that when a star is thus serving in place of the single slit source, the interference fringes are obliterated when $\alpha = \frac{1.22\,\lambda}{R}$, where α represents the angular diameter of the star (in radians), λ represents the wavelength of the light used, and R represents the distance between slits.

Michelson's method of increasing the effective slit distance by mounting movable 45° mirrors on a light rigid beam across the 40″ telescope at Yerkes was described, and plans were outlined for the use of the receiving mirrors at a considerably greater distance apart.

The fact that photography is not involved in this method was pointed out to be an advantage. It was shown, however, that the usefulness of the method is limited to those nearer stars whose distance can be determined accurately by the method of parallax.

Then were shown slides illustrating the wave-front explanation of double slit interference, the effects of varying the slit distances and the time of exposure, and the size of the source slit, the application of the method to the determination of the relative intensity of the stars of a binary system, the optical system of a reflector with a beam interferometer, and a photograph of such a beam mounting.

Members present were then given the opportunity to observe interference fringes with the use of scratched glass plates, two vertical incandescent wires serving as sources of light. This was followed by the usual brief period for the questioning of the speakers by members.

H. W. Fowler, *Secretary*.

RADIO TALKS OVER CFCT, VICTORIA, B.C.

By W. E. Harper

Big Stars

(February 15, 1938)

In the past few talks I have been speaking of stars which suffer some accident so that they expand to two or three hundred times their normal size and increase their luminosity several thousand-fold. These increases are only temporary and the expanding star soon relapses to its original size.

I wish to-night to speak of stars which in their normal condition are of enormous size. Stars are usually compared with our own star, the sun, so we must first learn its size. We can easily measure its angular size and find it to be a little over half a degree. About 350 suns placed edge to edge would stretch from the southern horizon up through the zenith and down to the northern horizon like a great necklace through an angle of 180 degrees. But this angular measure of half a degree cannot be converted into linear measure until we know the distance of the sun from us. Time fails me to explain how this quantity is determined but once its value of 93,000,000 miles is obtained it is easy to derive the linear diameter of the sun as 864,000 miles. Shall we say roughly it is slightly under a million miles.

The stars are suns like our own but appear simply as points of light because they are so far away. Were our sun at their average distance it would appear no brighter than they do. Some of them appear much brighter than others and this may be because they are intrinsically bigger and brighter or because they are nearer, or both. The distance of a star must be known before we can judge its brightness as compared with the sun. There are various ways of determining the distances of the stars and we shall assume that we know the distances of any stars we are discussing. It will give you a general idea of stellar distances if I tell you that light requires only eight minutes to reach us from the sun, but several years from the average bright star.

Let us take the well-known yellowish star Capella. We know its distance is 42 light-years, so we can calculate that it would be about 161 times the brightness of the sun were they at the same distance. And since they are both of a yellowish colour we know that their temperatures are about the same so that, area for area, their surfaces would be equally luminous. Then Capella's surface must be 160 times that of our sun or its diameter approximately 13 times the sun's. There are other considerations which modify these figures slightly but this gives the general idea.

But let us take a star of another colour to compare with our sun for size. Suppose we take the reddish star in Orion above the three forming the belt. We call it Betelgeuse. Its colour suggests a surface temperature of possibly 2500° as compared with 6000° for the sun. Consequently, area for area, the sun's surface would shine much more brightly than Betelgeuse. The ratio is

roughly four to one. From the measured distance of the Orion star we know it to be 2750 times the real luminosity of our sun. Keeping in mind the inferior radiating power of its surface we can deduce its diameter as 215,000,000 miles, about 250 times that of our sun.

In a similar way we study the very reddish star Antares seen low on the southern horizon in the early summer evenings. Its surface radiating power is even less than that of the Orion star so it must make up for its great intrinsic brightness by being enormously large. It has a diameter of about 400 million miles or nearly 500 times that of our sun. If it and the sun could be thought of as having the same centre, a portion of it would extend away out beyond the earth; indeed we would be buried more than half way down in its interior. This is no fanciful dream. These large dimensions were computed theoretically long before it was ever deemed possible actually to measure the same. The interferometer, a recently devised instrument, confirms these theoretical values in a striking way.

Intermediate between these two reddish stars, Betelgeuse and Antares, is a well-known variable star Mira, the wonderful, which rises to maximum brilliancy every eleven months. Its diameter is 250 million miles. Thus we have in millions of miles 215, 250 and 400 as diameters for these large stars. The densities, it must be added, are exceptionally low.

There is another way of discovering large stars. If they are binary it may happen that they will eclipse each other if the orbital plane happens to be oriented aright. Then from the duration of the eclipse coupled with the speed in the orbit the size of the components can be arrived at. A certain star Zeta Aurigae, whose orbit I determined several years ago, proves to be such an eclipsing binary. One of the components is an ordinary bluish white star; the other is a giant red one. Their period of revolution is 972 days and for about 38 days the blue one is hid behind the big red fellow as it moves about it in its orbit. This enables us to calculate that the diameter of the big red fellow as being 81 million miles or about 94 times the diameter of our sun.

This was the largest eclipsing star known until a few weeks ago. A news despatch from Chicago refers to the companion of the bright star Epsilon in the same constellation of Auriga as now holding the palm for size. It is reputed to be 3000 times the diameter of the sun. Here we must be forewarned. For thirty or more years this companion has been known to be the cause of the light-variation of the brighter component. The period of revolution of the pair is approximately 28 years and during the recent eclipse of the bright star by the very nebulous companion the Yerkes observers secured data which they interpret as evidence that the eclipsing body may be designated a star. Its temperature is given as 1000°, a value much lower than heretofore considered sufficient to cause a star to shine. The occulting body was formerly looked upon as a great swarm of loosely connected bodies like a flock of meteorites. If the body can qualify as a star, then it truly is the largest known to date.

Thus we have listed stars having diameters approximately 13, 250, 300, 500 and 3000 times that of our own sun. Next time I shall speak of little stars.

Little Stars

(March 15, 1938)

If we could visit the stars one by one we would find that in some features they are much alike while in others they are quite different. The vast range in size and intrinsic brightness would be most impressive. I spoke last month of large stars and we noted some examples of very tenuous stars whose diameters were three or four hundred times that of our sun. To-night I wish to deal with those at the other extreme—that is, those very much smaller than the sun.

For the most part we find these "giants" and "dwarfs" to be stars reddish in colour, indicative of a temperature of 2000°C. or possibly even as low as 1500°C. The general process of development would seem to be as follows. Starting as a vast tenuous mass like some of the stars described last month the star slowly condenses, increasing in temperature and surface luminosity. Though the surface area diminishes, this is offset by its greater brilliancy and the total luminosity remains more or less constant. Eventually there comes a time when energy is radiated away faster than it is formed through contraction and the star becomes both cooler and smaller, ending as a red dwarf. The process takes millions of years to complete, of course, and it would appear that about three stars out of every four of which we have any specific knowledge are becoming cooler as they contract. In technical terms they lie on the main sequence.

But not all the dwarfs are cool red stars. It seems to be the fate of some of them to collapse almost entirely. In these the atoms are completely crushed in upon themselves and enormous densities result. Such stars are known as "white dwarfs" since their temperatures are sufficiently high to yield a whitish colour. The number of these known to date is very, very limited.

When we look out upon a field of stars we cannot tell much about the actual distribution of giants and dwarfs in space because we can see the bright stars to much greater depths of space than is possible for faint ones. Dwarfs can be seen only in case they are near us. Of the 1500 brightest stars (that is the apparently brightest) in the sky only 100 are dwarfs, according to Joy, and of these only 15 are less luminous than the sun.

But it is a different story if we take a definite volume of space around us, sufficiently near so that dwarf stars can be recognized. The nearest star known to us is distant about 4½ light-years and if we take a sphere whose radius is 16 light-years there is not one giant among the 36 stars known to be within the distance. All are dwarfs on the main sequence and only four are intrinsically brighter than the sun. Of the others three are white dwarfs while the remainder are red dwarfs, some of them 30,000 times fainter than the sun. If the distribution throughout space is similar to that in the neighbourhood of the sun then there must be a preponderance of stars of low luminosity and our sun has a higher rank in the scale than that with which it is generally credited.

Let us take an example of a white dwarf. The very bright star Sirius, well-known to most people and now so prominent in the southern sky in the

early evenings, has a faint companion. The two are in mutual revolution about each other in a period of fifty years. The mass of the bright component is 2.5 times the sun while that of the faint component equals the sun. But there is a vast difference in their relative brightnesses, for the faint star is only one ten-thousandth as bright as Sirius itself. From the colour we can estimate its temperature and deduce its surface brilliancy. From this we can derive the surface area and diameter. The faint component has a diameter of only 29,000 miles, one-thirtieth that of the sun and about equal to that of the planet Uranus. But since it packs a mass equal to the sun within that volume, it must have a density 40,000 times that of water. It would be about all one could do to lift a thimbleful of the matter of which this white dwarf is composed. This startling fact has been confirmed in other ways.

So much for the small white dwarfs. With masses comparable to the sun they have diameters only one thirtieth as great. We next turn to the red dwarfs. Without investigation we cannot tell whether a certain reddish star is a giant or a dwarf. It may either be starting on its career as a giant nebulous agglomeration or have run its course through the aeons of time, and now, having radiated away its mass, is about to give up the ghost. We can differentiate between the two states if we can obtain its spectrum, for there are certain tell-tale markings in each star's analysed light that reveal at once whether the source of light is a giant or a dwarf star. If the reddish star is apparently too faint to secure its spectrum it may be possible to determine its distance and thus derive its real luminosity in that way. One indication of the distance of a star is given by what is called its "proper" or "cross" motion. Though such motions are exceedingly small they are detectable after 20 or 30 years and it is easily understood that the nearer stars would on the average have greater cross motions than the more distant ones.

In such ways we have come to recognize certain red stars as intrinsically faint and small. Barnard discovered one sending out 1/2500 of the light of the sun. In 1917 van Maanen discovered one sending out 1/6000 of the light of the sun and more recently he has shown that a star discovered by Wolf (359) gives out only 1/50,000 of the sun's light. Barnard's star is about the size of Jupiter, Wolf's star is like Uranus while van Maanen's is no bigger than the earth. In this last-mentioned star the atoms are crushed beyond recognition with the density 400,000 times that of water. A cubic inch of its material would weigh 7 tons. It should strictly be called a white dwarf as it has been classified as F_3.

Such are some of the more notable cases of small and intrinsically faint stars. They are very few in number and it is only within very recent years that they have been accepted as genuine members of the stellar universe.

The Royal Astronomical Society of Canada

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